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Clinical Investigation

PAEDIATRIC ANAESTHESIA

Precision of neuromuscular monitoring in paediatric patients: a randomised prospective agreement study of kinemyography and electromyography☆

Flora T. Scheffenbichler[1], Magdalena Marb[1], Bernhard Ulm[1,2], Anna S. Scholze[2], Sebastian F. N. Bode[3], Bettina Jungwirth[1], Manfred Blobner[1,4,*] and Sebastian Schmid[1]

[1]Department of Anaesthesiology and Intensive Care Medicine, Ulm University, Ulm, Germany, [2]Department of Anaesthesiology and Intensive Care Medicine, TUM School of Medicine and Health, Technical University of Munich, Munich, Germany, [3]Department of Paediatrics and Adolescent Medicine, Ulm University Medical Centre, Ulm, Germany and [4]Clinical Division of General Anaesthesia and Intensive Care Medicine, Department of Anaesthesia, Intensive Care Medicine and Pain Medicine, Medical University of Vienna, Vienna, Austria

*Corresponding author. E-mail: manfred.blobner@uni-ulm.de

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Abstract

Background: Quantitative neuromuscular monitoring in children remains challenging, particularly in weight and age categories without equipment certification. The study compared the precision of kinemyography and electromyography in children <5 yr of age.

Methods: Sixty-four children were stratified into neonates (≤44 weeks postmenstrual age), infants (44–58 weeks postmenstrual age), toddlers (>58 weeks postmenstrual age to ≤2 yr), and children (2–5 yr). Kinemyography and electromyography were applied to contralateral arms. Primary endpoints were precision of train-of-four ratios before rocuronium administration and after assumed complete recovery (i.e. after sugammadex administration). Precision was quantified using the repeatability coefficient, indicating the range within which a repeated train-of-four ratio is with 95% probability. A low repeatability coefficient indicates high precision.

Results: Median repeatability coefficients were 0.06 [IQR 0.03–0.10] for kinemyography and 0.06 [0.05–0.09] for electromyography (median difference 0.00 [95% confidence interval, CI −0.01 to 0.01]) at baseline and 0.04 [0.02–0.07] and 0.04 [0.03–0.06] after recovery (median difference 0.00 [−0.01 to 0.01]). Kinemyography precision was worse in non-certified use (<5 kg: 0.08 [0.05–0.11], ≥5 kg: 0.04 [0.02–0.06]; median difference 0.04 [0.02–0.05]), whereas electromyography performed similarly regardless of its certification (neonates 0.05 [0.03–0.11], others 0.06 [0.03–0.09]; median difference −0.01 [−0.04 to 0.05]). Train-of-four ratios <0.9 were more frequent in kinemyography than in electromyography (33% *vs* 16%, $P<0.05$).

Conclusions: Neither kinemyography nor electromyography was inferior to the other in terms of precision. Unlike kinemyography, electromyography remained precise even when applied below recommended age or weight limits. The importance of baseline values before rocuronium is underlined by the frequently measured train-of-four ratios of <0.9.

Clinical trial registration: ClinicalTrials.gov; NCT06062290 (registered August 15th, 2023).

Keywords: agreement study; electromyography; kinemyography; neuromuscular blockade; paediatric anaesthesia; precision; quantitative neuromuscular monitoring

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Editor's key points

- Quantitative neuromuscular monitoring in children is challenging because of the limited availability of certified devices and age-related differences in pharmacodynamics.
- This prospective randomised agreement study compared the precision of kinemyography and electromyography for monitoring neuromuscular function in response to rocuronium with sugammadex reversal in children <5 yr of age.
- The precision of kinemyography and electromyography did not show inferiority of either technique when used in children <5 yr of age.
- A higher frequency of train-of-four ratio <0.9 with kinemyography before administration of rocuronium could favour electromyography, but baseline measurements are nevertheless crucial for monitoring.

In paediatric patients, quantitative neuromuscular monitoring is challenging.[1,2] This is not surprising because of the limited availability of certified devices suitable for small fingers and forearms. Devices certified for adults often provide fluctuating and unreliable values in children, which is a critical limitation given the high variability of neuromuscular physiology and pharmacology in paediatric patients. Age-related differences in body composition and physiological function are major reasons for poor predictability in response to neuromuscular blocking drugs,[3,4] increasing the risk of incomplete neuromuscular recovery.[5] This underscores the need for precise quantitative neuromuscular monitoring in paediatric patients.

There are currently two techniques that are approved for paediatric patients, albeit with some limitations. A paediatric-sized kinemyography (KMG) sensor (NMT Mechanosensor, GE Healthcare, Helsinki, Finland) has been certified for body weights from 5 to 20 kg for several years.[6,7] Paediatric-sized electromyography (EMG) electrodes have recently been certified for use in children aged 28 days and older.[8–10] Expert consensus and guidelines from national and international paediatric associations support the use of currently uncertified medical devices for children to mitigate the risk of undertreatment.[11] However, the lack of evidence to inform clinical decision-making, particularly in the youngest and most vulnerable patients, is unacceptable.

This prospective non-inferiority study examined whether KMG and EMG (Tetragraph, *Senzime*, Uppsala, Sweden) are noninferior to each other in terms of their precision in children aged 0–5 yr, also including infants for whom neuromuscular monitoring devices are most often uncertified. Precision determines the range within which repeated measurements vary under unchanged conditions (repeatability), allowing discrimination between true physiological change and measurement variability.[12]

Methods

We conducted a prospective agreement study at a German university hospital in accordance with Good Clinical Practice and the Declaration of Helsinki, approved by the ethics committee of Ulm University (#70/23), and registered on ClinicalTrials.gov (NCT 06062290, August 15, 2023). The Guidelines for Reporting Reliability and Agreement Studies were followed (Supplementary Digital Content, GRASS Statement).[13] Data were protected in accordance with applicable law and hospital guidelines for data collection and storage.

Study cohort

We included children under 5 yr scheduled for noncardiac surgery with an ASA physical status ≤3 requiring general anaesthesia and neuromuscular block. Paediatric patients with contraindications to rocuronium or sugammadex administration, neuromuscular diseases, injuries impairing muscle or nerve function of both arms or children undergoing surgical procedures outside the operating theatre were not included. Informed written consent was obtained from both parents before anaesthesia.

Randomisation and blinding

Enrolment was conducted in blocks of 8, stratified by the four age groups: neonates (≤44 weeks postmenstrual age), infants (>44 to ≤58 weeks postmenstrual age), toddlers (>58 weeks postmenstrual age to ≤2 years), and children (>2 to <5 yr). The arm of the KMG measurement was randomly assigned. The study statistician (BU) was blinded to group allocation for analysis of the primary endpoints.

Anaesthesia

Anaesthesia care was performed in accordance with the department's standard of care. Vital sign monitoring (IntelliVue MX-600, Philips, Böblingen, Germany; Root, Masimo, Puchheim, Germany) was commenced after arrival in the operating room. After preoxygenation, anaesthesia was induced and maintained with sevoflurane by mask. The airway was secured with a supraglottic airway device during baseline measurements of neuromuscular monitoring. If appropriate, the anaesthetised children received additional regional or local anaesthesia.

Investigational procedure

After skin degreasing, both KMG and EMG were applied to the randomly assigned arm by the study personnel (FTS, MM) on all patients. Forearms were positioned at 90° to the body and elbows at 90–120°, to ensure stable measuring conditions without interfering with the surgery. For KMG and EMG, which were positioned on both arms of each patient to enable simultaneous measurements, train-of-four (TOF) mode was set to a 20 s measurement interval and an automatic search for the supramaximal current at a pulse width of 200 μs. To maintain temperature, the arms were covered with a blanket.

For KMG, two Ag/AgCl electrodes (NMT Electrode, Solid gel, GE Healthcare, Helsinki, Finland) were placed over the ulnar nerve. The piezoelectric sensor strip and the fingers were secured with adhesive tape to stabilise measurement conditions (Fig. 1a and c). The automated search for supramaximal stimulation was limited to 70 mA. The electric signal of the piezoelectric strip was recorded at a sampling rate of 300 Hz and downsampled to 40 Hz for analysis.

The EMG electrode (TetraSens Paediatric, Senzime, Uppsala, Sweden) was placed over the ulnar nerve for stimulation and over the hypothenar muscle for measurement of the muscle potential. The reference electrode was attached to

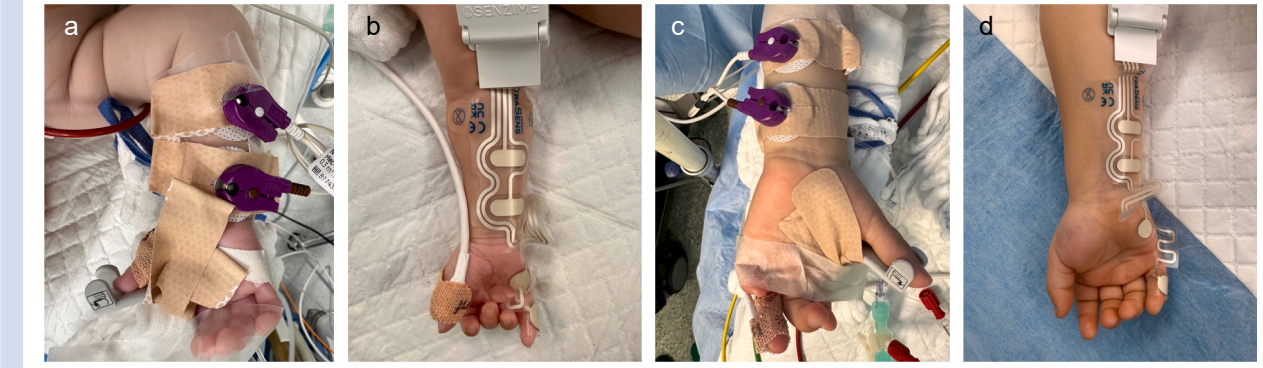


Fig 1. Application of the NMT Mechanosensor (GE Healthcare, a and c) and the Tetrasens Paediatric sensor array (b and d) on an infant and a child.

the lateral side of the proximal interphalangeal joint of the fifth finger (Fig. 1b and d). The automated search for the supramaximal stimulation pulse required an EMG response of >2 mV. If the supramaximal stimulus could not be obtained at a current amplitude of 60 mA with a pulse width of 200 μs, the automatic search increased the pulse width to 300 μs and continued the search with a current amplitude >40 mA. The twitch response was sampled and analysed at a rate of 1 kHz.

After simultaneous baseline measurements of 2 min, rocuronium 0.2 mg kg^{-1} was administered. After 3 min, the study physician assessed whether the TOF count had reached the target value of ≤2 by tactile sense. If not, increments of rocuronium 0.1 mg kg^{-1} were administered until the target value was reached. If tracheal intubation was required during surgery, it was performed at this point. Because a considerable proportion of paediatric patients in our clinical routine do not achieve recovery to a TOF value >0.9 with an adult-sized acceleromyography at the end of surgery, all children were administered sugammadex 2 mg kg^{-1} to rule out residual neuromuscular blockade regardless of the TOF ratio or end tidal sevoflurane concentration at the end of anaesthesia (Supplementary Fig. 1).

Endpoints

The primary endpoints were precision at baseline and precision after complete neuromuscular recovery, expressed by repeatability coefficients. The repeatability coefficient is a measure indicating the range in which the absolute differences between two repeated measurements fall with 95% probability. A low repeatability coefficient, therefore, indicates high precision. Complete recovery was assumed when the TOF ratio did not further increase after sugammadex administration.

Secondary endpoints were agreement between simultaneously recorded KMG and EMG TOF ratio measurements during baseline and during the entire neuromuscular recovery (TOF ratios >0.2). Exploratory endpoints included precision at TOF ratios >0.2. For analyses evaluating complete neuromuscular recovery, a period of 120 s after sugammadex administration was excluded to avoid confounding by rapid pharmacological recovery. Clinical safety endpoints were postoperative respiratory complications in the recovery room.[14] The safe use of both devices was assessed by inspecting the forearms and hands for skin lesions, redness, or pressure points in the recovery room and at discharge. Postoperative pain was assessed using the 'Kindliche Unbehagens- und Schmerz' Scale.[15]

Sample size

Noninferiority of precision was assumed if the repeatability coefficient of the TOF ratios of one device was not greater than that of the TOF ratios of the other device. A difference of 0.01 between the repeatability coefficients of EMG and KMG was assumed acceptable, as it is the smallest visible difference on available quantitative monitoring devices. Assuming 0.01 as the critical difference, an expected repeatability coefficient of 0.05,[16,17] a significance level $P=0.025$ (sharing the two-sided alpha of 5% for the two repeatability coefficients, one at baseline and one at complete recovery), and a power of 80%, confirmation of noninferiority using F-tests needed 290 pairs of measurements. Because the baseline measurement period lasted 2 min with a measurement frequency of 20 s, six measurements per device were possible, resulting in a total of 50 children required to obtain a minimum of 290 pairs. To obtain equally sized groups, 13 children per age group were necessary. To compensate for 3 expected dropouts per group, we included 16 children per age group. This is also consistent with the repeated measures approach in agreement studies, where the number of pairs per participant must be less than the number of participants.[18] In addition, the study protocol specified that five patients would be enrolled in the run-in phase. These patients underwent the entire clinical trajectory but were not included in the statistical analysis.

Statistical analysis

The primary endpoints were precision, expressed as the repeatability coefficient, which was measured independently using a one-way analysis of variance on sets of consecutive TOF ratios for both EMG- and KMG-measured TOF ratios. The 95% repeatability coefficient was calculated as $1.96\sqrt{2}\hat{\sigma}_w$, where $\hat{\sigma}_w$ was defined as the standard deviation of analysis of variance residuals.[16,17,19–21] The primary analyses tested the noninferiority of KMG and EMG precision to each other. Margins of 0.01 were defined as acceptable. A monitoring technique was considered noninferior if the lower and upper limits

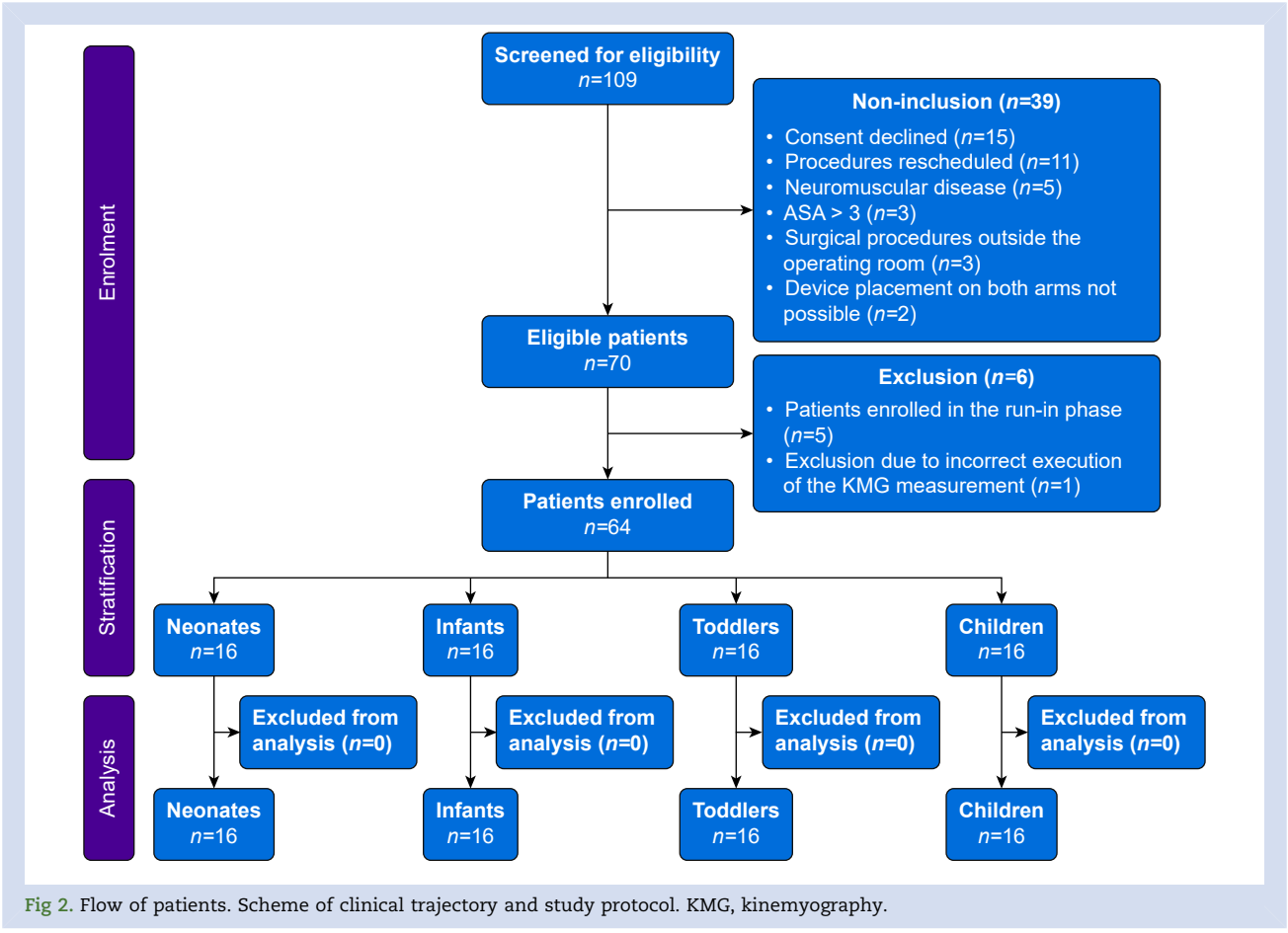


Fig 2. Flow of patients. Scheme of clinical trajectory and study protocol. KMG, kinemyography.

of the confidence interval for the effect difference did not exceed the margins.

The Shapiro-Wilk test was applied to evaluate the normal distribution as such. In case of non-normal distribution, the 95% confidence intervals were calculated using bootstrap resampling with 2000 iterations.[22] The least significant change of each device was calculated using *repeatability coefficient* × $\sqrt{2}$.[12] For agreement analyses, Bland-Altman analysis for repeated measures was used.[18] The limits of agreement were calculated as $|\overline{d}| = 1.96 \cdot \sqrt{\sigma_d^2 + \sigma_w^2}$ where $\overline{d}$ is defined as the mean difference between the devices, σ_d as the between-subject standard deviation and σ_w is defined as the between-subject standard deviation. A Bland-Altman diagram was created. Cohen's standardised difference was calculated for comparing qualitative (tactile) monitoring and quantitative monitoring (KMG and EMG, respectively). For comparisons between KMG and EMG, the Wilcoxon signed-rank test was used for paired comparisons, and the McNemar test for paired frequencies. For exploratory age-group comparisons, the Kruskal–Wallis test and the χ^2 test were used. To compare the precision between age- and weight-related certified and noncertified use of each device, we performed respective subgroup analyses using an unpaired Mann-Whitney *U* test.

Data are presented as median [interquartile range (IQR)] or as numbers (%). A *P*-value of 0.05 was considered statistically significant. Median differences are presented with their 95% confidence intervals (95% CI). All analyses were performed using the statistical software R (version 4.3.3, R Foundation for Statistical Computing, Vienna, Austria).

Results

A total of 64 patients under 5 yr were enrolled between September 2023 and May 2024 (Fig. 2). The median age was 5 [IQR 2–36] months, and the median weight was 7.6 [IQR 4.0–13.3] kg (Table 1). To achieve a TOF count ≤2, 46 children required rocuronium 0.2 mg kg^{-1}; 14 children required one increment, and four children required three increments of 0.1 mg kg^{-1} each (Supplementary Table S1). Two of 64 children were administered rocuronium increments during surgery. Abdominal surgery included urachal cyst resection, oesophagogastroduodenoscopy and other visceral surgeries. Urologic surgery included nephrectomy, circumcision, hypospadias repair and orchidopexy. End tidal sevoflurane concentration was significantly higher during baseline measurements compared with measurements after complete recovery in all age groups (*P*<0.001; Table 1).

Neuromuscular monitoring was established in all patients. In 10 of 64 with KMG and in three of 64 with EMG, the supramaximal stimulation current could not be identified on the first attempt, so the procedure had to be repeated (Table 2). In five of 16 neonates (31%) and three of 16 infants (19%), the automatic search for a supramaximal current pulse of the EMG included an extension of the pulse width to 300 μs in addition to the maximum current of 60 mA (Table 2).

Table 1 Characteristics of study cohort. Data are presented as median [interquartile range] or absolute numbers (%). *at surgery; p.m., postmenstrual; n/a, not applicable.

Characteristics	All (*n*=64)	Neonates ≤44 weeks p.m. (*n*=16)	Infants >44 to ≤58 weeks p.m. (*n*=16)	Toddlers >58 weeks p.m. to ≤2 years (*n*=16)	Children >2 to <5 years (*n*=16)
Weight (kg)	7.6 [4.0–13.3]	3.2 [3.0–3.7]	5.1 [4.4–6.0]	11.4 [9.3–12.4]	16.8 [15.0–19.0]
Chronological age (months)	5 [2–36]	1 [1–2]	3 [2–4]	16 [12–26]	53 [44–55]
Gestational age* (weeks p.m.)	n/a	41 [39–42]	49 [46–52]	n/a	n/a
Sex					
Male	54 (84%)	16 (100%)	14 (88%)	13 (81%)	11 (69%)
Female	10 (16%)	0	2 (13%)	3 (19%)	5 (31%)
ASA physical status					
1	19 (30%)	0	0	11 (69%)	8 (50%)
2	26 (41%)	0	15 (94%)	5 (31%)	6 (38%)
3	19 (30%)	16 (100%)	1 (6%)	0	2 (13%)
Admission					
Inpatient	38 (59%)	15 (94%)	9 (56%)	6 (38%)	8 (50%)
Day-case	26 (41%)	1 (6%)	7 (44%)	10 (63%)	8 (50%)
Surgical procedure					
Abdominal surgery	21 (33%)	3 (19%)	4 (25%)	4 (25%)	12 (75%)
Hernia repair	24 (38%)	10 (63%)	10 (63%)	3 (19%)	1 (6%)
Urologic surgery	14 (22%)	1 (6%)	1 (6%)	9 (56%)	3 (19%)
Neurosurgery	2 (3%)	1 (6%)	1 (6%)	0	0
Other	3 (5%)	0	0	2 (13%)	1 (6%)
End tidal sevoflurane during baseline (vol %)	3.6 [3.2–4.0]	4.0 [3.4–5.0]	3.9 [3.5–4.1]	3.5 [3.2–4.0]	3.1 [2.6–3.7]
End tidal sevoflurane after recovery (vol %)	2.9 [2.1–3.2]	2.9 [1.9–3.0]	3.0 [2.2–3.3]	3.0 [2.6–3.2]	2.9 [2.1–3.0]
Caudal epidural block	49 (77%)	10 (63%)	15 (94%)	14 (88%)	10 (63%)

Table 2 Search for the supramaximal stimulus, twitch responses at baseline and recovery. Data are presented as median [interquartile range] or absolute number (%). kAU, 10^3 arbitrary units; EMG amp, amplitude of the compound muscle action potential; EMG dur, duration of the compound muscle action potential of electromyography (EMG). * $P<0.05$; comparisons between kinemyography (KMG) and EMG. † Within-technique comparisons between age groups. ‡ The automatic search for a supramaximal stimulus of the EMG includes widening the pulse to 300 μs. With the KMG, the pulse can be manually widened to 300 μs. ¶ Train-of-four (TOF) ratios before rocuronium administration. § TOF ratios after 2 min after sugammadex administration. ** TOF ratios have recovered to baseline levels if their mean following sugammadex was within or above the 95% confidence interval of its individual baseline.

	All (*n*=64)	Neonates (*n*=16)	Infants (*n*=16)	Toddlers (*n*=16)	Children (*n*=16)	*P* value†
More than one attempt to find supramaximal stimulation current						
KMG	10 (15.6%)	5 (31.3%)	4 (25.0%)	0	1 (6.3%)	0.048
EMG	3 (4.7%)*	2 (12.5%)	1 (6.3%)	0	0	0.6
Supramaximal stimulation (current)						
KMG (mA)	49 [35–64]	64 [58–64]	64 [55–64]	40 [35–40]	29 [29–29]	<0.001
EMG (mA)	40 [40–55]	60 [50–60]	50 [40–55]	40 [40–45]	40 [30–40]	<0.001
Supramaximal stimulation (300 μs pulse width)‡						
KMG	0	0	0	0	0	n.a.
EMG	8 (13%)*	5 (31%)	3 (19%)	0	0	0.028
Twitch response at baseline						
KMG (kAU)	4.4 [2.3–6.1]	2.2 [1.3–3.6]	2.8 [2.3–4.8]	4.8 [3.0–5.3]	8.5 [5.4–9.7]	<0.001
EMG amp (mV)	5.0 [4.1–6.5]	4.7 [4.0–5.6]	4.2 [3.5–4.7]	5.5 [4.6–6.5]	6.9 [6.0–8.5]	<0.001
TOF ratio at baseline¶						
KMG	0.95 [0.87–0.98]	0.84 [0.79–0.96]	0.93 [0.88–0.96]	0.96 [0.88–0.98]	0.98 [0.95–1.00]	<0.001
EMG	0.99 [0.93–1.01]*	0.93 [0.79–0.98]	0.97 [0.91–0.99]	1.01 [1.00–1.02]	1.01 [1.00–1.03]	<0.001
Patients with TOF ratio >0.9 at baseline¶						
KMG	43 (67%)	4 (25%)	11 (69%)	12 (75%)	16 (100%)	<0.001
EMG	54 (84%)*	10 (63%)	13 (81%)	15 (94%)	16 (100%)	0.27
TOF ratio after sugammadex (2 mg kg^{-1})§						
KMG	0.93 [0.83–0.97]	0.83 [0.74–0.92]	0.86 [0.78–0.94]	0.97 [0.94–0.99]	0.96 [0.93–0.99]	<0.001
EMG	0.99 [0.93–1.01]*	1.01 [1.00–1.03]	1.01 [1.00–1.02]	0.93 [0.80–0.98]	0.97 [0.91–0.99]	<0.001
Patients with TOF ratio >0.9 after sugammadex (2 mg kg^{-1})§						
KMG	38 (59%)	4 (25%)	7 (44%)	14 (88%)	13 (81%)	<0.001
EMG	58 (91%)*	12 (75%)	16 (100%)	15 (94%)	15 (94%)	0.15
Patients with TOF ratios after sugammadex recovered to baseline TOF ratios**						
KMG	46 (72%)	9 (56%)	12 (75%)	13 (81%)	12 (75%)	>0.9
EMG	56 (88%)*	14 (88%)	13 (81%)	14 (88%)	15 (94%)	0.6

Stimulation current significantly decreased with patient age for both KMG and EMG. Furthermore, the KMG baseline amplitude increased with age from a median of 2.2 kilo-arbitrary units (kAU) in neonates to 8.5 kAU in children >2 yr. The increase of the EMG baseline amplitude with older age ranged from a median of 4.7 mV to 6.9 mV (Table 2).

At the end of anaesthesia, 38 patients (59%) reached a TOF ratio of >0.9 with KMG and 58 (91%) with EMG ($P<0.05$). With EMG, the TOF ratios recovered to baseline levels in 56 children, whereas with KMG, this was the case in only 46 children ($P<0.05$); this difference was particularly prominent in neonates and infants (Table 2).

Precision

At baseline, the median repeatability coefficient was 0.06 [IQR 0.03–0.10] for KMG and 0.06 [IQR 0.05–0.09] for EMG, with a median difference of 0.00 (95% CI −0.01 to 0.01) between TOF ratios of both techniques. The baseline median least significant change was 0.05 [IQR 0.03–0.10] for KMG and 0.06 [IQR 0.05–0.08] for EMG.

Once recovery was complete, there was also no difference in the repeatability coefficients between KMG (0.04 [IQR 0.02–0.07]) and EMG (0.04 [IQR 0.03–0.06]), with a median difference of 0.00 (95% CI −0.01 to 0.01). After complete recovery, the median least significant change was 0.05 [IQR 0.03–0.06] for KMG and 0.06 [IQR 0.04–0.08] for EMG.

Repeatability coefficients of baseline and after recovery within the respective age groups are shown in Fig. 3a and b. Because the median differences of the repeatability coefficients crossed the non-inferiority margins, the two techniques were not inferior to each other at baseline or after complete recovery (Fig. 3c).

During the entire neuromuscular recovery with TOF ratios >0.2, median repeatability coefficients were 0.19 [IQR 0.13–0.32] with KMG and 0.19 [IQR 0.12–0.28] with EMG. Across all age groups, precision during recovery decreased with decreasing age, peaking in neonates who showed a median repeatability coefficient of 0.32 [IQR 0.18–0.42] when measured by KMG and 0.26 [IQR 0.17–0.34] when measured by EMG (Supplementary Table S2).

Baseline repeatability coefficients of children for whom KMG is not certified were higher compared with those for whom the procedure is certified (<5 kg: 0.080 [IQR 0.05–0.11]; >5 kg: 0.04 [IQR 0.02–0.06]) with a median difference of 0.04 (95% CI 0.02–0.05). The baseline repeatability coefficients of children for whom the EMG is certified were comparable to those for whom it is not certified (neonates 0.050 [IQR 0.03–0.11], all others 0.06 [IQR 0.03–0.09]), with a median difference of −0.01 (95% CI −0.04 to 0.05).

Agreement

A total of 6905 pairs of TOF ratios were evaluated for agreement. At baseline and during the entire neuromuscular recovery (TOF ratio >0.2), TOF ratios were higher with EMG than with KMG. The bias was 0.05 at baseline and 0.03 for TOF ratios >0.2 in all patients (Fig. 4).

Difference between tactile evaluation of the TOF count and qualitative monitoring

Quantitative KMG monitoring showed a median TOF count of 4 [IQR 1–4], whereas the concomitant qualitative measurement was a median count of 0 [IQR 0–3]. EMG displayed a median TOF count of 0 [IQR 0–2] when, by tactile sense, a median of 0 [IQR 0–2] was observed. Cohen's standardised difference (95% confidence interval) between tactile and KMG-measured TOF count was moderate to high but minimal between tactile and EMG-measured TOF count [0.75 (95% CI 0.53–0.98) *vs* 0.12 (95% CI −0.10 to 0.34)] in all children and also in all age groups (Supplementary Table S3).

Postoperative evaluation

In the recovery room, mean oxygen saturation was 96% (3%). One neonate and one toddler required an oxygen mask, which improved saturation. Oxygen supplementation was only temporary for both children, who were discharged from the recovery room without it. No child showed signs of respiratory distress, upper airway obstruction, use of respiratory support muscles, or aspiration or had to be reintubated.

The median 'Kindliche Unbehagens- und Schmerz' Scale was 0 [IQR 0–0], meaning no signs of pain, and no patients had skin abnormalities on either arm. Transient erythema at the electrode position occurred in four patients after EMG and in three after KMG monitoring.

Discussion

This agreement study comparing the precision of KMG and EMG did not show inferiority of either technique when used in patients below 5 yr of age. For both devices, the repeatability coefficients were 0.04 before rocuronium administration and 0.06 after complete recovery. A coefficient of repeatability of 0.04 indicates that, following a TOF ratio of 0.90, with a probability of 95%, the next TOF ratio will lie between 0.86 and 0.94. When not certified, the precision of KMG was lower compared with its certified use, whereas the precision of EMG was similar irrespective of certification.

There is limited scientific evidence comparing quantitative neuromuscular monitoring techniques in paediatric patients.[23] Three studies have been conducted in children over 2 yr of age comparing acceleromyography or KMG with EMG.[6,7,24] None of the available studies evaluated precision. Only one study examined agreement of TOF ratios between EMG and acceleromyography, showing a bias of 0.03 and limits of agreement ranging from −0.26 to 0.32,[24] comparable with the bias of 0.05 with similarly wide limits of agreement between EMG and KMG in our study. The differences between EMG and KMG were most pronounced in preterm and term neonates and in children weighing ~20 kg.

Skin resistance is lower in neonates and infants because their immature stratum corneum lacks keratin and lipid lamellae.[25,26] Therefore, the higher supramaximal currents observed in both KMG and EMG in neonates and infants are unexpected. Possibly, the electric field penetrates less deeply because of the small distance between the electrodes, despite the higher current density of the small paediatric electrodes.[27–29] More likely, peripheral nerves in preterm and term neonates are incompletely myelinated,[30,31] which substantially elevates the threshold for supramaximal stimulation.[32]

If a current of 60 mA does not produce a maximal response, the EMG device automatically widens the stimulation pulse from 200 μs to 300 μs. The stronger electrical pulses[33] and the electrodes optimised for paediatric use probably explain the higher primary success rate of the supramaximal current search with EMG *vs* KMG (95% *vs*

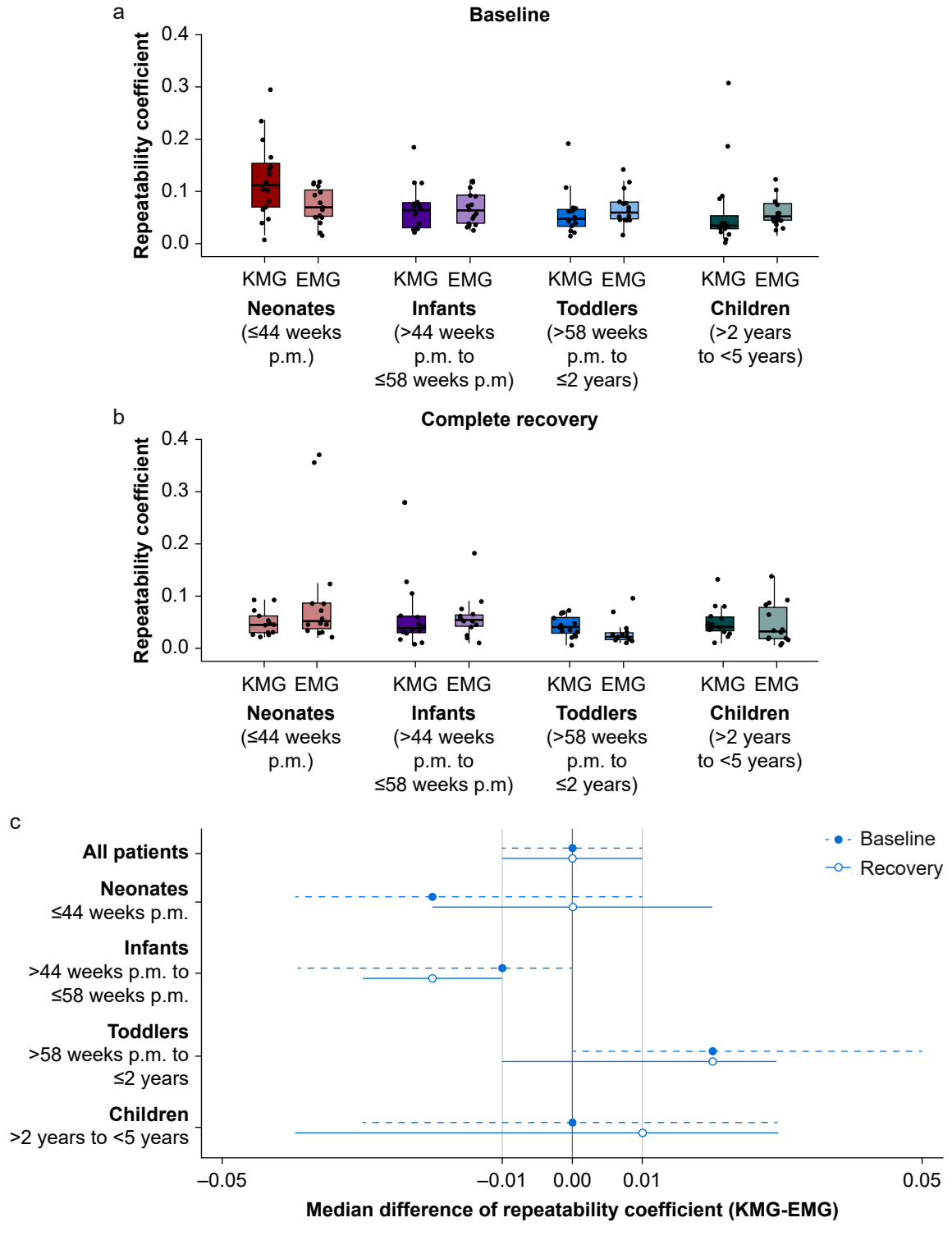


Fig 3. Box plots and individual repeatability coefficients (points) at baseline (a) and after complete recovery (b) of the predefined age groups. (c) Noninferiority plot of all patients and the respective age groups at baseline (dashed line) and after complete neuromuscular recovery (solid line) showing the median differences of repeatability coefficients between kinemyography (KMG) and electromyography (EMG) with 95% confidence intervals (2000 bootstrap samples). Positive values indicate greater precision of EMG, whereas negative values indicate greater precision of KMG. Comparisons of all patients were not inferior to each other. Noninferiority plots for age groups are provided for exploratory purposes. p.m., postmenstrual.

a

Baseline	No. of observations	Bias (95% CI)	Lower limit of agreement	Upper limit of agreement
All	607	0.05 (0.03 to 0.06)	–0.30 (–0.32 to –0.27)	0.39 (0.37 to 0.42)
Neonates	155	0.03 (0.01 to 0.06)	–0.32 (–0.37 to –0.27)	0.39 (0.34 to 0.44)
Infants	141	0.02 (–0.00 to 0.04)	–0.21 (–0.24 to –0.17)	0.24 (0.21 to 0.27)
Toddlers	134	0.03 (0.01 to 0.04)	–0.14 (–0.17 to –0.12)	0.20 (0.17 to 0.22)
Children	177	0.10 (0.06 to 0.13)	–0.38 (–0.44 to –0.32)	0.57 (0.51 to 0.63)
TOF ratio >0.2				
All	6298	0.03 (0.03 to 0.03)	–0.21 (–0.22 to –0.21)	0.27 (0.27 to 0.28)
Neonates	638	0.03 (0.02 to 0.05)	–0.31 (–0.33 to –0.29)	0.38 (0.35 to 0.40)
Infants	1426	0.06 (0.05 to 0.07)	–0.23 (–0.24 to –0.21)	0.35 (0.34 to 0.37)
Toddlers	1378	–0.01 (–0.02 to –0.01)	–0.23 (–0.24 to –0.22)	0.20 (0.19 to 0.21)
Children	2856	0.03 (0.03 to 0.03)	–0.15 (–0.16 to –0.15)	0.22 (0.21 to 0.22)

b

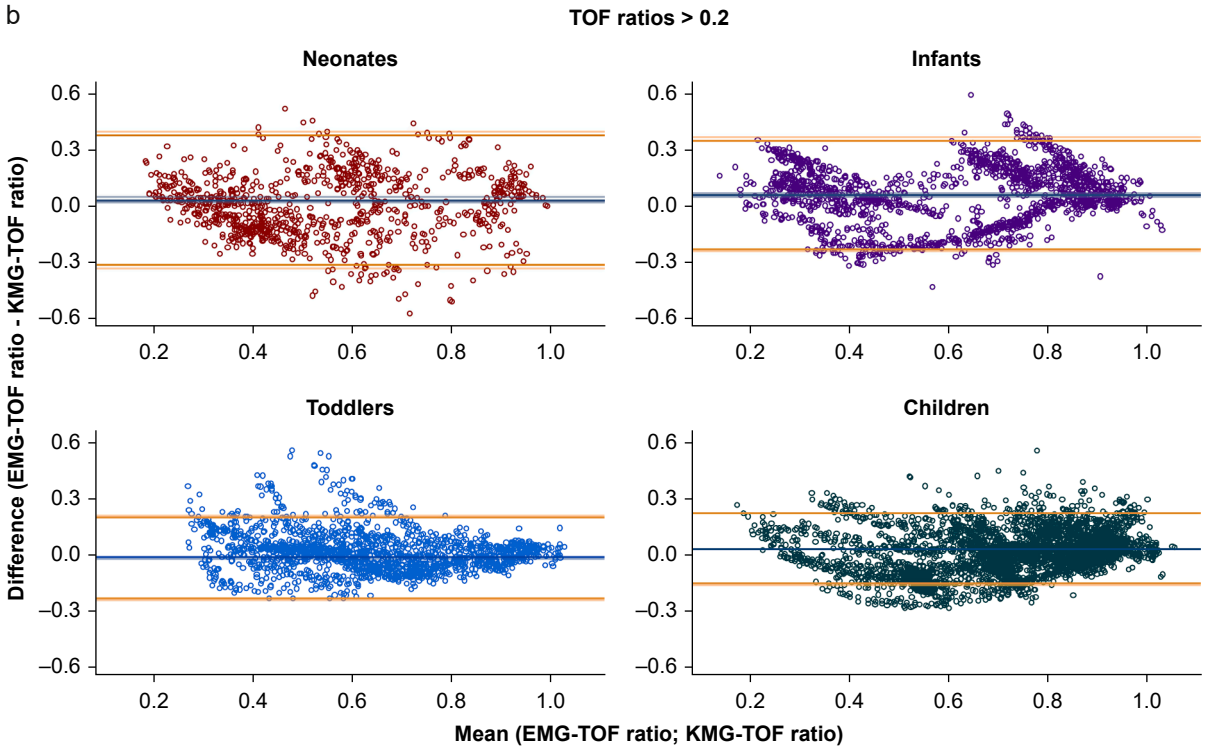


Fig 4. (a) Bias and limits of agreement from Bland-Altman analysis during baseline and during neuromuscular recovery (TOF ratios >0.2) for the entire cohort and age-related subgroups. The limits of agreement are defined as the range in which 95% of the differences between measurements fall. (b) Bland-Altman plot showing agreement between all KMG-obtained train-of-four (TOF) ratios >0.2 and electromyography (EMG) TOF ratios in the predefined age groups. The blue line represents the bias, and the yellow lines represent the lower and upper limits of agreement.

84%). Importantly; of the 8 of 32 neonates and infants stimulated in this way, none showed any skin irritation. However, the higher degree of automation is likely to be welcomed by anaesthesia providers.

The amplitude of the compound muscle action potential increased by 60% between neonates and children. Because the number of muscle fibres does not increase after birth,[34] there must be another explanation. The concentration of acetylcholine receptors at the motor endplate is largely established by the 25th week of gestation.[35] At birth, the transition from neonatal to adult acetylcholine receptors is almost complete, although the proportion of adult receptor subtypes continues to increase.[36,37] These maturation processes, however, do not alter the single-fibre action potential, which is all-or-none. Incomplete myelination of the ulnar nerve, however, might cause temporal dispersion of the incoming axonal action potential, possibly resulting in a decreased amplitude (Table 2) and increased duration of the compound muscle action potential in neonates and infants compared with older children.[38]

Muscles grow through an increase in the cross-sectional area and length of fibres,[39] and strength through motor learning and training.[40] This explains the roughly 4-fold increase in thumb adduction velocity during baseline measurements with increasing age, which might have exceeded the linear measurement range of the piezoelectric sensor strip, thereby reducing precision. The KMG sensor is therefore only approved for children weighing 5 to 20 kg.

Sevoflurane potentiates rocuronium-induced neuromuscular block.[41,42] In adults, a TOF ratio <0.9 only develops with neuromuscular disorders or very high sevoflurane concentrations.[43] It was therefore striking that TOF ratios <0.9 were present at baseline in neonates and infants but not in older children.

Decrement (i.e. TOF ratio <0.9) is attributed to presynaptic fatigue of acetylcholine release, which is either because of an insufficient synthesis secondary to immature mitochondrial function[44] or an impaired synaptic allocation of acetylcholine,[45] both of which reduce the margin of safety of neuromuscular transmission. As sevoflurane, used for anaesthesia induction, depolarises axonal mitochondria[46] and allosterically inhibits presynaptic acetylcholine receptors,[47] it might have induced the TOF ratios <0.9 in preterm and term neonates at baseline. Because end tidal sevoflurane concentrations were higher during baseline compared with those after complete recovery, it is unlikely that sevoflurane contributed to an increased incidence of TOF ratios <0.9 at complete recovery. In any case, this observation highlights the importance of baseline measurements.

We more frequently observed TOF ratios <0.9 with KMG, both during baseline measurements and after reversal with sugammadex, primarily in neonates. We can only speculate about the nature of this observation. As a direct effect of sevoflurane on muscle contraction is unlikely based on available data, the weak stimulus response in babies <5 kg can lead to additional measurement imprecision.

The extent of doubt surrounding the quality of neuromuscular monitoring in children becomes evident from studies validating their quantitative measurements with qualitative results.[1,24] Although we do not endorse qualitative neuromuscular monitoring in any way, consistency between the measured TOF count and that obtained by tactile sense strengthens anaesthesia providers' confidence. The better agreement between palpated and measured TOF count by EMG compared with KMG in our paediatric cohort aligns with reports in adults, where EMG outperformed acceleromyography in this regard.[48] The discrepancy between KMG and tactile TOF count in preterm and newborn infants could be attributed to the infant's thumb not having sufficient force to bend the KMG sensor enough to exceed the detection threshold of the piezoelectric strip. Conversely, a KMG displaying a TOF count of 4, while EMG and tactile counts are zero, might indicate background noise or direct muscle stimulation. Both can lead to incorrect decisions when using KMG on newborns.

This study has some limitations. (1) The sample size was calculated for the entire cohort of children aged 0 to 5 yr. The age-related subgroup analyses are exploratory and lay the foundation for upcoming confirmatory studies in neonates and infants. (2) The study staff could not be blinded because of the nature of the study intervention. (3) We induced and maintained anaesthesia with sevoflurane in all patients, which is why we cannot rule out that the TOF ratio <0.9 would also have occurred in the baseline measurements without sevoflurane. However, recovery to TOF ratios above their individual baseline values is unlikely. (4) The sampling rate of the KMG does not allow for analysis of maturing neuromuscular function. However, increasing the sampling rate of the Tetragraph™ to over 1 kHz would be desirable in order to gain more insight into the immature compound muscle action potential typical of neonates.

Conclusions

The precision of EMG and KMG in children below 5 yr of age was not inferior to that of the other technique. Given the general acceptance of a TOF ratio of 0.9 as the threshold for unimpaired neuromuscular function, the higher frequency of TOF ratios <0.9 observed with KMG before the administration of rocuronium could contribute to the preference for EMG, especially in infants for whom the devices are not certified. Baseline measurements are nevertheless crucial to obtain a reference TOF ratio for complete neuromuscular function.

Authors' contributions

Study design and conceptualisation: FTS, MB and SS
Data collection and manuscript drafting: FTS and MM
Statistical analysis: BU
Supervised of the study: BJ, MB and SS
Project administration: FTS
Manuscript revision and final approval: all authors

Declarations of interest

FTS received a research grant from the Else-Kröner-Fresenius Stiftung (Bad Homburg vor der Höhe, Germany). MB received fees for consultancy or lectures from GE Healthcare (Helsinki, Finland), Grünenthal (Aachen, Germany), Senzime (Landshut, Germany), MIPM (Mammendorf, Germany), and HW Pharmaconsulting (Moosbach, Germany). All remaining authors declare no conflict of interest.

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Appendix A. Supplementary data

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References

1. Faulk DJ, Austin TM, Thomas JJ, Strupp K, Macrae AW, Yaster M. A survey of the society for pediatric anesthesia on the use, monitoring, and antagonism of neuromuscular blockade. *Anesth Analg* 2021; **132**: 1518–26
2. Ozgen ZSU. Neuromuscular blockade monitoring in pediatric patients. *Anesth Pain Med (Seoul)* 2024; **19**(Suppl. 1): S12–24
3. Fisher DM. Neuromuscular blocking agents in paediatric anaesthesia. *Br J Anaesth* 1999; **83**: 58–64
4. Goudsouzian NG. Maturation of neuromuscular transmission in the infant. *Br J Anaesth* 1980; **52**: 205–14

5. Scheffenbichler FT, Rudolph MI, Friedrich S, et al. Effects of high neuromuscular blocking agent dose on postoperative respiratory complications in infants and children. *Acta Anaesthesiol Scand* 2020; **64**: 156–67
6. Gaffar EA, Fattah SA, Atef HM, Omera MA, Abdel-Aziz MA. Kinemyography (KMG) versus electromyography (EMG) neuromuscular monitoring in pediatric patients receiving cisatracurium during general anesthesia. *Egypt J Anaesth* 2013; **29**: 247–53
7. Jung W, Hwang M, Won YJ, Lim BG, Kong MH, Lee IO. Comparison of clinical validation of acceleromyography and electromyography in children who were administered rocuronium during general anesthesia: a prospective double-blinded randomized study. *Korean J Anesthesiol* 2016; **69**: 21–6
8. Tobias JD, Epstein RH, Rice-Weimer J, Yemele Kitio SA, Brull SJ, Kalsotra S. Pediatric intraoperative electromyographic responses at the adductor pollicis and flexor hallucis brevis muscles: a prospective, comparative analysis. *Anesth Analg* 2024; **139**: 36–43
9. Chaney A, Villalobos EE, Rice-Weimer J, Tobias JD. Intraoperative electromyographic monitoring in children less than 1 year of age. *Paediatr Anaesth* 2025; **35**: 934–9
10. Iwasaki H, Takahoko K, Yamagata C, et al. Comparison of supramaximal currents obtained by acceleromyography and electromyography for monitoring the adductor pollicis muscle in pediatric patients. *J Clin Monit Comput* 2025; **39**: 625–30
11. Section on Cardiology and Cardiac Surgery, Section on Orthopaedics. Off-label use of medical devices in children. *Pediatrics* 2017; **139**, e20163439
12. Cecconi M, Rhodes A, Poloniecki J, Della Rocca G, Grounds RM. Bench-to-bedside review: the importance of the precision of the reference technique in method comparison studies–with specific reference to the measurement of cardiac output. *Crit Care* 2009; **13**: 201
13. Kottner J, Audigé L, Brorson S, et al. Guidelines for reporting reliability and agreement studies (GRRAS) were proposed. *J Clin Epidemiol* 2011; **64**: 96–106
14. Murphy GS, Szokol JW, Marymont JH, et al. Intraoperative acceleromyographic monitoring reduces the risk of residual neuromuscular blockade and adverse respiratory events in the postanesthesia care unit. *Anesthesiology* 2008; **109**: 389–98
15. Büttner W, Finke W, Hilleke M, Reckert S, Vsianska L, Brambrink A. [Development of an observational scale for assessment of postoperative pain in infants]. *Anasthesiol Intensivmed Notfallmed Schmerzther* 1998; **33**: 353–61
16. Liang SS, Stewart PA, Phillips S. An ipsilateral comparison of acceleromyography and electromyography during recovery from nondepolarizing neuromuscular block under general anesthesia in humans. *Anesth Analg* 2013; **117**: 373–9
17. Khandkar C, Liang S, Phillips S, Lee CY, Stewart PA. Comparison of kinemyography and electromyography during spontaneous recovery from non-depolarising neuromuscular blockade. *Anaesth Intensive Care* 2016; **44**: 745–51
18. Bland JM, Altman DG. Agreement between methods of measurement with multiple observations per individual. *J Biopharm Stat* 2007; **17**: 571–82
19. Stewart PA, Freelander N, Liang S, Heller G, Phillips S. Comparison of electromyography and kinemyography during recovery from non-depolarising neuromuscular blockade. *Anaesth Intensive Care* 2014; **42**: 378–84
20. Scheffenbichler FT, Ulm B, Borgstedt L, et al. Precision of electromyography according to the calibration approach of neuromuscular monitoring: a randomised prospective agreement study. *J Clin Monit Comput* 2025; **39**: 1047–56
21. Scholze AS, Ulm B, Kretsch N, Jungwirth B, Blobner M, Scheffenbichler FT. A single-centre, randomised comparison of the performance and safety of a novel mechanomyography sensor with electromyography. *Br J Anaesth* 2026; **136**: 906–14
22. Efron B. Bootstrap methods: another look at the JackKnife. *Ann Statist* 1979; **7**: 1–26
23. Veyckemans F, Debouche S, Kaufmann J, et al. 2025 ESAIC and ESPA Guidelines on neuromuscular block in anaesthetised children: Indications, monitoring and reversal. *Eur J Anaesthesiol* 2026; **43**: 295–323
24. Ansermino JM, Sanderson PM, Bevan JC, Bevan DR. Acceleromyography improves detection of residual neuromuscular blockade in children. *Can J Anaesth* 1996; **43**: 589–94
25. Kalia YN, Nonato LB, Lund CH, Guy RH. Development of skin barrier function in premature infants. *J Invest Dermatol* 1998; **111**: 320–6
26. Muramatsu K, Hirose S, Yukitake K, Ogata H, Mitsudome A, Oda T. Relationship between maturation of the skin and electrical skin resistance. *Pediatr Res* 1987; **21**: 21–4
27. Nemes R, Németh E, Szatmári KA, et al. Hand size measurements in children aged 1–15 years to help the development of pediatric electromyography sensors for neuromuscular monitoring. *J Clin Med* 2025; **14**: 7462
28. Alon G, Kantor G, Ho HS. Effects of electrode size on basic excitatory responses and on selected stimulus parameters. *J Orthop Sports Phys Ther* 1994; **20**: 29–35
29. Du J, Morales A, Paknahad J, et al. Electrode spacing and current distribution in electrical stimulation of peripheral nerve: a computational modeling study using realistic nerve models. *Annu Int Conf IEEE Eng Med Biol Soc* 2021; **2021**: 4416–9
30. Jansen L, Bürke N, West E, Wurster J, Broser PJ. Analysis of the maturation of the median nerve in preterm-born children during the first 3 years of life using high-resolution nerve ultrasound imaging. *Brain Behav* 2025; **15**, e70954
31. Jenny C, Lütschg J, Broser PJ. Change in cross-sectional area of the median nerve with age in neonates, infants and children analyzed by high-resolution ultrasound imaging. *Eur J Paediatr Neurol* 2020; **29**: 137–43
32. Bostock H. The strength-duration relationship for excitation of myelinated nerve: computed dependence on membrane parameters. *J Physiol* 1983; **341**: 59–74
33. Holsheimer J, Dijkstra EA, Demeulemeester H, Nuttin B. Chronaxie calculated from current-duration and voltage-duration data. *J Neurosci Methods* 2000; **97**: 45–50
34. Dayanidhi S, Lieber RL. Skeletal muscle satellite cells: mediators of muscle growth during development and implications for developmental disorders. *Muscle Nerve* 2014; **50**: 723–32
35. Hesselmans LF, Jennekens FG, Van den Oord CJ, Veldman H, Vincent A. Development of innervation of skeletal muscle fibers in man: relation to acetylcholine receptors. *Anat Rec* 1993; **236**: 553–62

36. Mishina M, Takai T, Imoto K, et al. Molecular distinction between fetal and adult forms of muscle acetylcholine receptor. *Nature* 1986; **321**: 406–11
37. Li H, Teng J, Hibbs RE. Structural switch in acetylcholine receptors in developing muscle. *Nature* 2024; **632**: 1174–80
38. Barkhaus PE, Nandedkar SD, de Carvalho M, Swash M, Stålberg EV. Revisiting the compound muscle action potential (CMAP). *Clin Neurophysiol Pract* 2024; **9**: 176–200
39. Lawlor MW, Margeta M, Jones KA, et al. Establishment of normal myofiber size distribution in children and young adults. *J Neuropathol Exp Neurol* 2025; **84**: 1159–73
40. Dotan R, Mitchell C, Cohen R, Klentrou P, Gabriel D, Falk B. Child-adult differences in muscle activation–a review. *Pediatr Exerc Sci* 2012; **24**: 2–21
41. Woloszczuk-Gebicka B, Wyska E, Grabowski T. Sevoflurane increases fade of neuromuscular response to TOF stimulation following rocuronium administration in children. A PK/PD analysis. *Paediatr Anaesth* 2007; **17**: 637–46
42. Eikermann M, Hunkemöller I, Peine L, et al. Optimal rocuronium dose for intubation during inhalation induction with sevoflurane in children. *Br J Anaesth* 2002; **89**: 277–81
43. Nitahara K, Sugi Y, Higa K, Shono S, Hamada T. Neuromuscular effects of sevoflurane in myasthenia gravis patients. *Br J Anaesth* 2007; **98**: 337–41
44. Peng J, Ramatchandirin B, Pearah A, Maheshwari A, He L. Development and functions of mitochondria in early life. *Newborn (Clarksville)* 2022; **1**: 131–41
45. Martyn JA, Fagerlund MJ, Eriksson LI. Basic principles of neuromuscular transmission. *Anaesthesia* 2009; **64**(Suppl. 1): 1–9
46. Tang Y, Zucker RS. Mitochondrial involvement in post-tetanic potentiation of synaptic transmission. *Neuron* 1997; **18**: 483–91
47. Scheller M, Bufler J, Schneck H, Kochs E, Franke C. Isoflurane and sevoflurane interact with the nicotinic acetylcholine receptor channels in micromolar concentrations. *Anesthesiology* 1997; **86**: 118–27
48. Bowdle A, Bussey L, Michaelsen K, et al. Counting train-of-four twitch response: comparison of palpation to mechanomyography, acceleromyography, and electromyography. *Br J Anaesth* 2020; **124**: 712–7

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